Optical Plume Anomaly Detection Engine Diagnostic Filtering System

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From the early days of rocket engine development, engineers have intently observed the exhaust plume during test and in actual flight—their trained eye seeking out a spectral signature of a healthy, properly operating propulsion system. During each observation, this spectral signature is compared with real-time performance and integrated in the "mind's eye" to pick up on anomalies or glitches that would indicate improper operation. Several years ago, MSFC engineers began a serious, more sophisticated look at techniques for detecting anomalies in the operation of the space shuttle main engine through observation of the exhaust plume. These efforts have resulted in considerable progress in the physics of observational devices and have provided encouragement relative to the potential value of such a capability. This success has led to the point of definition of the Optical Plume Anomaly Detection system. State-of-the-art technology in anomaly detection spectroscopy has demonstrated the ability to discern trace amounts (parts per billion) of metals involved in the space shuttle main engine's plume.

However, once these trace amounts are detected, what is the proper process for extracting valid and useful information? The defined process—the Optical Plume Anomaly Detection Engine Diagnostic Filtering System—is an aggressive effort not only to address the initial analysis of the myriad of data, but also to ultimately bring the detection system to future rocket engines as a viable tool for real-time health monitoring. A few of the major tasks within the program include preprocessing algorithms, neural net development of real-time quantification of species, and validation of spectroscopic/atomic models (fig. 109).

The area of model validation is of primary importance. The MSFC team for this effort seeks to validate its systems using plume-seeding data from the space shuttle main engine and the Diagnostic Test Facility. If good performance for analyses of

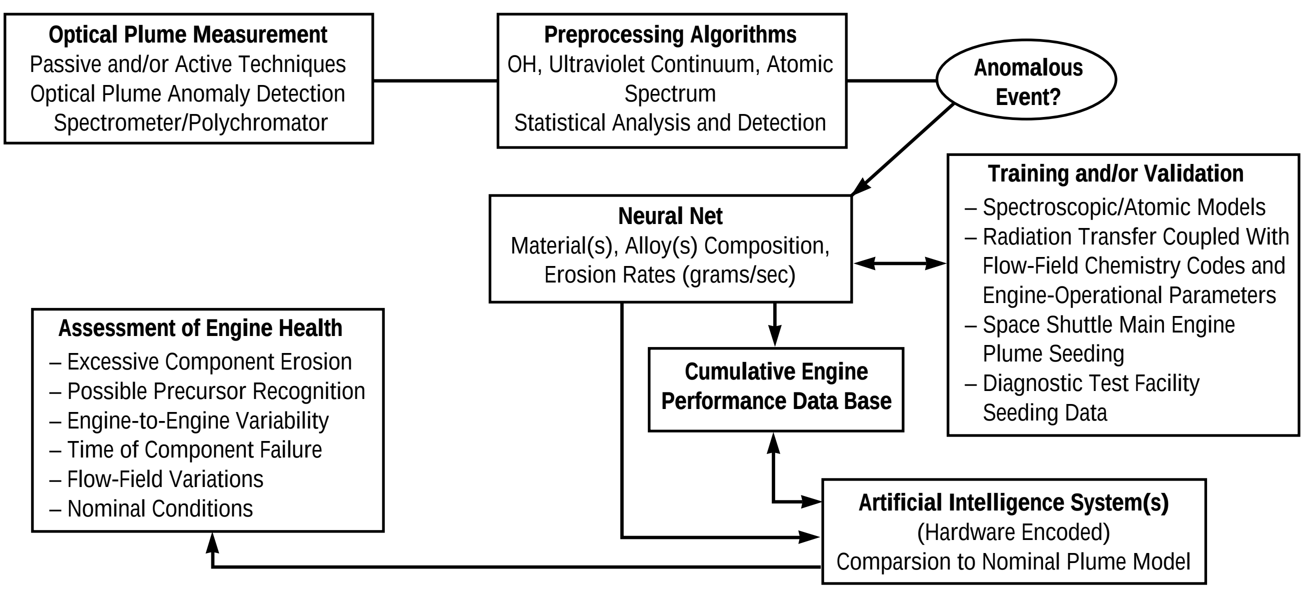

FIGURE 109.—Proposed Optical Plume Anomaly Detection Engine Diagnostic Filtering System process path.

spectral data from both engines can be achieved, then confidence can be placed in the physics, plume codes, and data processing, rather than using seeding data from one source as a calibration for the other. This form of self-consistent validation methodology, supported by team members from the Arnold Engineering Development Center in Tullahoma, Tennessee, will provide versatile spectral analysis systems to meet future demands for application to different rocket propulsion systems and different instrumentation for in-flight or ground-level measurements of spontaneous emission and stimulated emission/absorption of atoms. Recent success with seeding the flow of the shuttle's main engine at MSFC's Technology Test-Bed with a known quantity of substance affords the team with direct validation data for the main engine and also allows confirmation of secondary validation using Diagnostic Test Facility spectral data.

Before exhaust plume spectra can be analyzed for optical activity of atomic species, one must remove the baseline or discriminate between atomic transitions from spectral shapes and emission features normally found in the nominal baseline plume. In the shuttle main engine, one finds extremely high overtone excitation in the (0,0) and associated harmonics as well as a continuum region of emission that extends from the blue, visible far- into the near-ultraviolet spectrum. Preprocessing algorithms developed by Ames Research Center have attempted to address these issues. Initially, the data are registered in angstrom units that, in turn, allow correlation of anomaly detection data across tests and detection of emissions near the "noise level" or in the active OH region of the signal. Statistical tools are in place that characterize the detectability of elements of interest during transient and main-stage periods of a test with a 99-percent confidence level.

Test TTB036 (reference fig. 110 for depiction of various metals of interest) was the first test of the Pratt & Whitney fuel turbopump at the Technology Test-Bed. Propulsion engineers were interested in possible loss of cobalt-based "rub-stop" material. (Cobalt is not an element normally seen during Technology Test-Bed tests, but is clearly present in the anomaly detection spectral plot.) Essentially, with the click of a button, 4,096 data points are compared and statistically evaluated for each 0.5 second of data. Each test-bed test is an average of 170 seconds in duration. Other tools permit animation of data and engine data correlation on-line.

The Ames Research Center has also created an optimization routine to correlate neural net predictions with given spectral data sets. Radial basis function neural nets are under development at the University of Alabama in Tuscaloosa. Initially, multiple networks will be trained with the spectral model and compared to Diagnostic Test Facility data. Once an iterative process between model and neural network developers has produced a first set of "reasonable networks" and a validated spectral model has been achieved using Diagnostic Test Facility and space shuttle main engine data as previously mentioned, most robust networks can be trained quickly.

The neural network approach was chosen to address future needs for real-time applications. The spectral model takes species concentrations and produces a theoretical spectrum. However, the goal is to solve the inverse problem: given a measured spectrum, determine the "correct" specie concentrations. In previous applications of line-by-line codes used to determine specie number densities from path-integrated emission/absorption measurements, this problem is solved by linearized least-squares methods for minimizing the root-mean-square difference between the measured and predicted spectrum. However, while least-squares methods work well for narrow wavelength ranges in a posttest environment where real-time response is not an issue, the requirements of real-time response preclude this method due to generally long processing times. The University of Alabama has developed a solution to the inverse problem using neural networks that "learn" how the spectral line-by-line model works. Basically, the time-consuming computational part is performed pretest, and may take many hours, but the finished product can perform the inverse problem in real time, on the order of milliseconds, with no special hardware.

While other somewhat similar tasks may be underway, research indicates that the present MSFC-guided team of phenomenologists and spectroscopists from the Arnold Engineering Development Center, university professors, graduate students, Ames Research Center, and MSFC's own personnel will provide the best opportunity for the successful application of optical plume anomaly

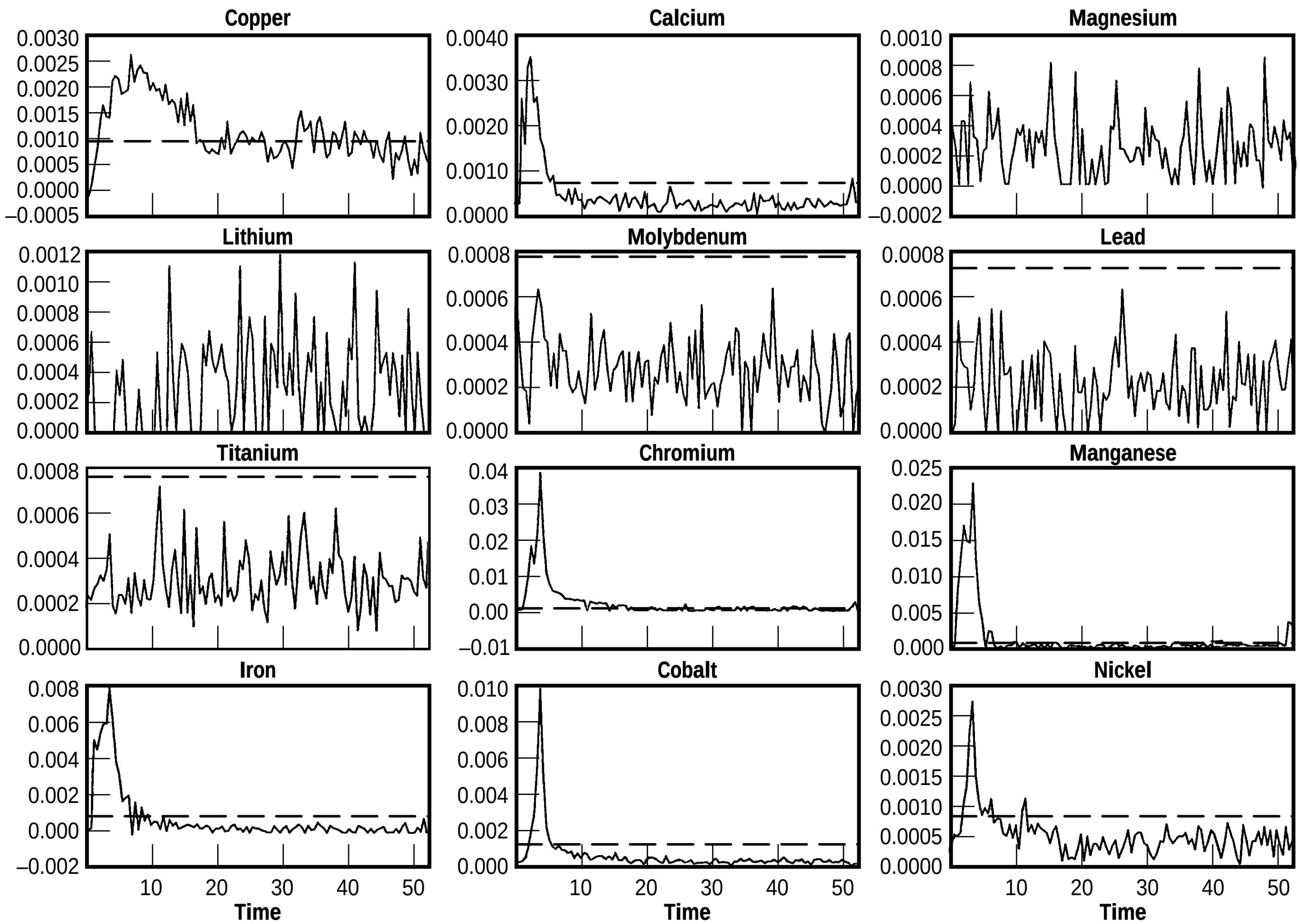

FIGURE 110.—Metals for test TTB036.

detection to future rocket engine operations. To date, the program has provided educational support through various grants to ten graduate and undergraduate students over the past few years.

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